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Regional assessment of the hydropower potential of rivers in West Africa

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Abstract

In this study the theoretical hydropower potential of all rivers in West Africa was assessed. The study domain covers 5 Mio km². For more than 500,000 river reaches the theoretical hydropower potential was computed from channel slope and mean annual discharge simulated by a water balance model. The model was calibrated with observed discharge at 410 gauges, using precipitation and potential evapotranspiration data as inputs. Possible changes in future discharge were assessed by driving the water balance model with climate projections of 15 Regional Climate Models for two emission scenarios of the CORDEX-Africa ensemble.

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Keywords: hydropower potential, West Africa, water balance modelling, climate change, CORDEX-Africa

1. Introduction

The 15 countries of the Economic Community of West African States (ECOWAS) face a constant shortage of energy supply, which limits economic growth. Currently there are about 50 operational hydropower plants and 40 more are under construction or refurbishment. The ECOWAS Centre for Renewable Energy and Energy Efficiency (ECREEE) was created to promote the development of sustainable energy generation including wind, solar and

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hydro. The potential for future hydropower development – especially for small-scale plants in rural areas – is assumed to be large, but exact data are missing.

The objective of this study is to support the energy initiatives of ECREEE by assessing the theoretical hydropower potential of all rivers in West Africa. This assessment is not limited to large rivers, but also focuses on small rivers for small-scale hydropower development.

The hydropower potential of a river depends on channel slope and mean annual discharge. Channel slope can be computed from digital elevation models with Geographic Information Systems (GIS). However, in large areas there is a lack of discharge observations. Therefore, in this study an annual water balance model was applied to simulate discharge. As hydropower plants are investments with a lifetime of several decades we also assessed possible changes in future discharge due to climate change.

The paper is structured as follows:

- Study area and data basis
- Water balance modelling
- Climate change impact assessment
- Theoretical hydropower potential
- Conclusions and outlook

2. Study area and data basis

This study focusses on all river basins in the 15 countries of ECOWAS in West Africa (Fig. 1). The climate ranges from tropical humid near the Gulf of Guinea to arid in the Sahara in the north. The study area covers about 5 Mio km² including 500,000 river reaches. Major river basins include Niger, Volta, and Senegal.

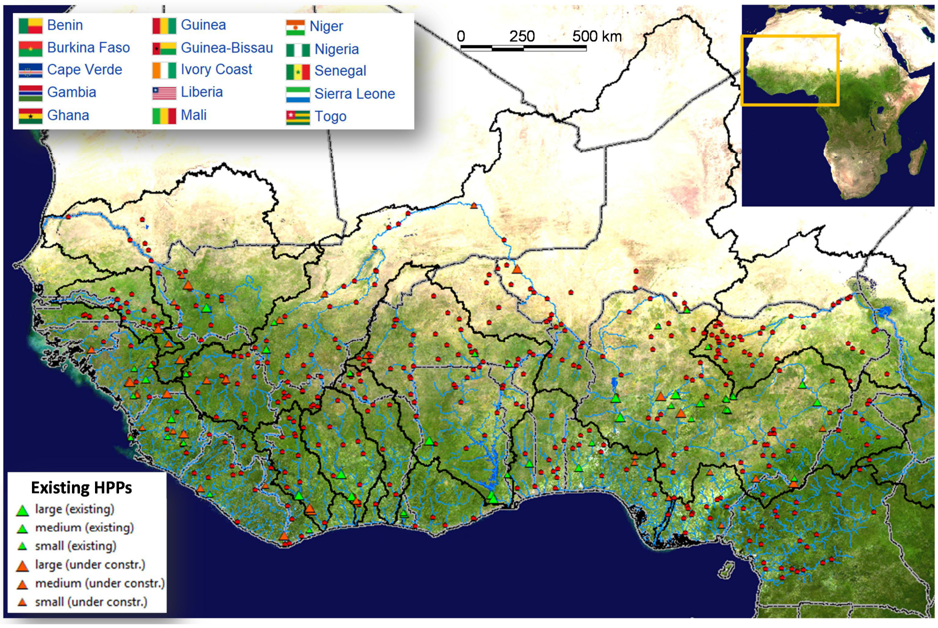

Fig. 1. Study area in West Africa. Blue lines: major rivers. Black lines: major basin divides. Grey lines: Country borders. Red circles: used gauges. Coloured background: satellite image showing vegetated areas in green. Triangles: Existing hydropower plants (HPP) with classification according to installed capacity: small (1-30 MW), medium (30-100 MW), large (> 100 MW).

The main data sources for this study are listed in Table 1. For the same data type there are often several different data sources. The different data sources were merged or – in the case of conflicting data – decisions had to be made which data set to keep. For precipitation data GPCC were used for the period 1951-2010 and TRMM for 1998-2014, whereas RFE data were removed due to poor reliability in the Fouta Djallon highlands in Guinea, which is the headwater region for the Niger and Senegal rivers. A comparison between potential evapotranspiration data sets showed that the station-based CLIMWAT data set showed considerably higher values in Cote d'Ivoire compared to the gridded data set of CRU. Therefore, CRU values were increased in this region to better correspond with CLIMWAT data. After comparing longitudinal river profiles extracted from three different elevation models it was decided to only keep the Hydrosheds 3s unconditioned DEM for further processing. Hydrosheds 15s flow direction grid was used for delineating the river network.

Observed discharge data are the most important and unfortunately also most problematic data source. Overall, data were pre-processed for 410 gauges (see Fig. 1), which is a small number of gauges for such a large region. Several of the gauges were misplaced due to incorrect coordinates (e.g. error by full degree latitude, insufficient number of coordinate decimal points for accurate geo-referencing, etc.). As a consequence, all gauges were manually checked using location description (gauge name, river name, and catchment area) and finally all gauges were manually snapped to the river network. Fig. 2 visualizes the starting and ending dates of the obtained discharge data from GRDC. The best data availability is from 1950-1990, whereas there are only few gauges included in the GRDC data set for the recent years 1998-2014. Additional data for about 50 gauges were provided by National Hydrological Services and River Basin Organizations. Most of the 410 observed discharge time-series are affected by frequent and prolonged data gaps. More problematic than clearly marked data gaps were duplicate values in subsequent years and severely biased data due to outdated rating curves, which are sometimes extremely difficult to detect. Monthly discharge time-series of all gauges were visually screened with neighboring gauges for (a) filling of data gaps (e.g. 0 values in dry season) and (b) removal of apparently biased values. Monthly time-series were aggregated to annual time-series for the calibration of the annual water balance model.

In summary, the observed discharge data contain very valuable hydrological information, but the data have to be interpreted with caution due to possible remaining biases after pre-processing. In addition, also possible biases in the used precipitation products introduce uncertainty in the simulation results.

Table 1. Main data sources

Data type	Source
Observed discharge	Global Runoff Data Centre (GRDC), National Hydrological Services, River Basin Organizations
Precipitation	Global Precipitation Climatology Centre (GPCC) gridded from station data, Tropical Rainfall Measurement Mission (TRMM 3B42) satellite based, Rainfall Estimator (RFE, FEWS-NET) satellite based
Potential evapotranspiration	Climatic Research Unit (CRU), CLIMWAT for CROPWAT (FAO)
Air temperature	Climatic Research Unit (CRU)
Digital elevation model	Unconditioned 3s Hydrosheds DEM (SRTM filled), Conditioned 3s Hydrosheds DEM (SRTM filled & stream burning), ASTER
River network	15s flow direction grid of Hydrosheds

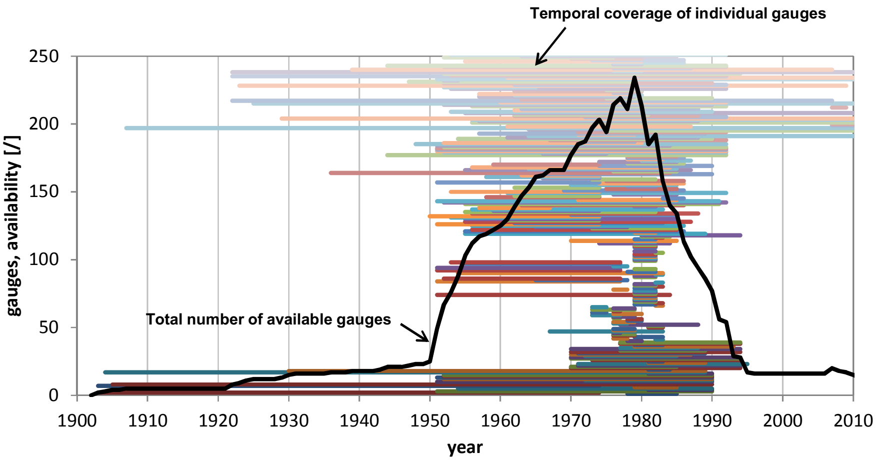

Fig. 2. Temporal coverage of observed daily discharge data at of GRDC. The coloured lines show the start and end of the observation periods (display limited to 250 out of 361 GRDC gauges), without considering data gaps. Black line shows the total number of available gauges (out of 361 GRDC gauges), with considering data gaps.

3. Water balance modelling

An annual water balance model was applied to estimate annual discharge in 500,000 reaches of the river network in West Africa. For the local sub-catchment of each river reach actual evapotranspiration is estimated with the Budyko curve [1] and runoff is computed from the water balance equation (assuming storage change is negligible). We used the formulation of the Budyko curve according to Choudhury [2], which requires specification of a single parameter to describe the shape of the Budyko curve (see Eq. 1). Inputs to the water balance model are precipitation and potential evapotranspiration. In the model, runoff (units of mm/y) is converted to local discharge (units of m³/s) by multiplication with local sub-catchment area of the reach. Local discharge is aggregated along the river network to compute discharge. At 40 locations substantial losses in discharge are accounted for due to flood plain evaporation (e.g. Inner Niger Delta in Mali, Yobe floodplain in Nigeria) and diversions for irrigation (e.g. in Sokoto River basin in Nigeria).

$$\frac{ETA}{P} = \left[1 + \left(\frac{ETP}{P} \right)^{-c} \right]^{-1/c} \tag{1}$$

where ETA is annual evapotranspiration in mm, P is annual precipitation in mm, ETP is annual potential evapotranspiration in mm, and c is a dimensionless parameter (with a typical range of 1.0 to 5.0).

Observed discharge data of 410 gauges were used for a regional calibration of the Budyko curve parameter. Manual calibration was assisted by automatic optimization. Parameter optimization (minimizing bias between simulated and observed discharge) was used to identify regions with similar parameter values. However, the optimized parameters values were not used in the final model to avoid overfitting to potentially biased discharge data. Instead, in the manual calibration regions with the same parameter values were defined, with the aim to obtain a regionally consistent parameter distribution, which also reflects regional variations in land-cover, soils, and climate. This approach also enabled to manually assign Budyko curve parameter values to ungauged basins.

Even though the application of the Budyko curve is originally intended for long-term mean annual water balance studies, the water balance model was applied for annual time-series from 1950-2014 (i.e. simulation of individual years). This enabled comparison of simulated and observed annual hydrographs (Fig. 3) and also facilitated computation of annual means of simulated and observed values (Fig. 4), where each gauge has a different observation period. In general, the water balance model yields unbiased discharge simulations (Fig. 4). For individual gauges the difference between simulated and observed mean annual discharge can be attributed to several factors:

- Simulation bias due to insufficient model structure, parameter values, and/or input data.
- Biased observed discharge data.
- Incorrect geo-referencing of gauges.

As outlined in the previous section, correct geo-referencing of gauges was a major issue in the data pre-processing. As an illustrative example, Fig. 4 includes one gauge with still incorrect geo-referencing. The gauge is misplaced at a small tributary, even though the correct location is most likely at the large, nearby Taraba River (Nigeria). For the final application of the model, biased observed discharge data and incorrect geo-referencing of gauges are not of concern, as only simulated discharge values are used for the hydropower potential estimation.

The model calibration mainly focused on the period 1950-1990 using GPCC precipitation data, as in this period the availability of observed discharge data is highest (see Fig. 2). For the final estimation of mean annual discharge in each reach the model is applied with TRMM precipitation data for the period 1998-2014. The comparison of simulation results in the overlapping period 1998-2010 shows that GPCC and TRMM yield quite similar results when considering mean annual discharge (see Fig. 3).

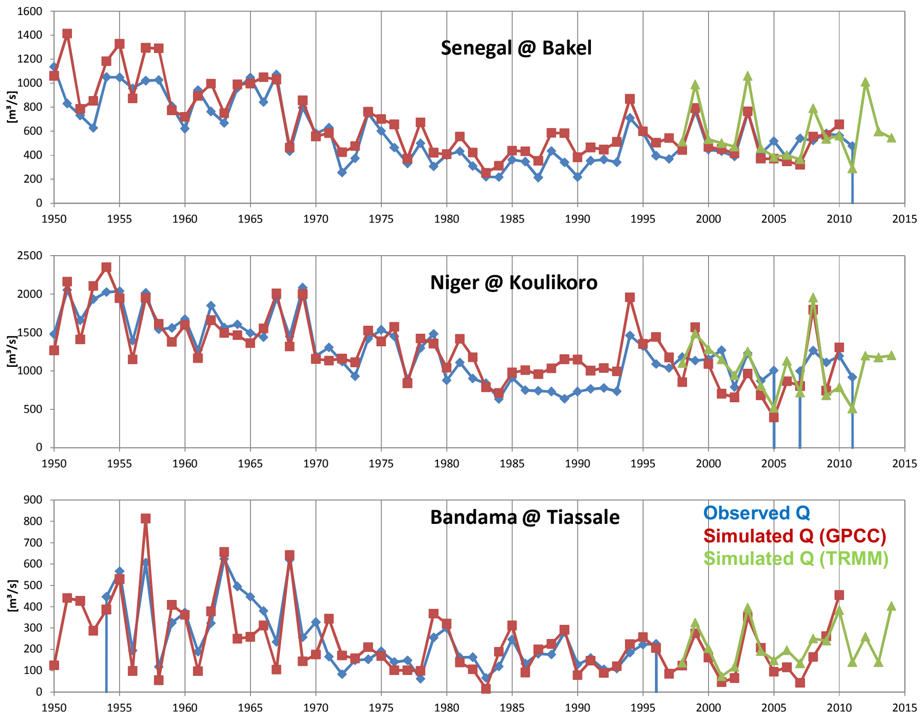

Fig. 3. Historical variations of discharge at three selected rivers. Comparison of simulated and observed (blue) discharge due to variations in annual rainfall. Simulation results using GPCC (red) and TRMM (green) rainfall data.

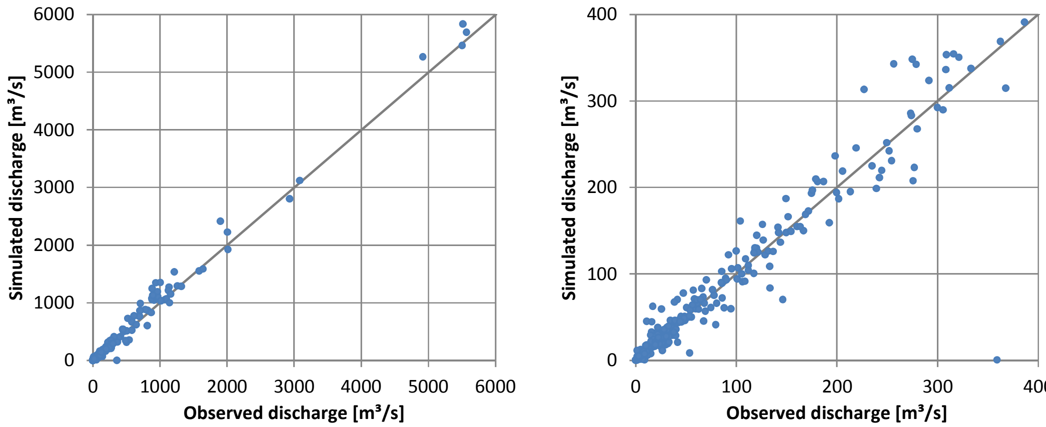

Fig. 4. Comparison of simulated and observed long-term mean annual discharge at 410 gauges. Evaluation period depends on observed discharge data availability in the period 1950-2014. Left: All 410 gauges. Right: Zoom on values below 400 m³/s. The outlier in the right figure with observed discharge of 360 m³/s but almost 0 m³/s simulated discharge is due to incorrect geo-referencing of a gauge at the Taraba River in Nigeria (i.e. the gauge coordinates are incorrect misplacing the gauge at a small tributary).

4. Climate change impact assessment

As hydropower plants are investments with a lifetime of several decades there is concern that climate change could have negative impacts on future hydropower generation (see e.g. [3]). To address these concerns climate change impacts on future discharge were assessed in this study. To this end the water balance model was driven with climate change signals based on projections of 15 Regional Climate Models of the CORDEX-Africa ensemble, which represents the most detailed climate projections currently available for Africa. Two Representative Concentration Pathways RCP4.5 and RCP8.5 were considered, thus yielding a total of 30 climate model runs.

The RCM precipitation and air temperature data were processed for 1350 sub-basins with a median size of 3000 km² covering the whole study area. The annual time-series data 1950-2100 were smoothed with 11-year moving average to enable more robust calculation of long-term trends. Climate change signals were computed between the reference period 1998-2014 and two future periods (2026-2045, 2046-2065).

The climate change signals of the two future periods were used to drive the water balance model under climate change scenarios with the delta change method. Temperature climate change signals (°C) were converted to potential evapotranspiration increase (%) based on sensitivity tests with the CROPWAT model of FAO (based on the Penman-Monteith method). Overall the water balance model was run 60 times (30 RCM runs times two future periods). For each river reach (500,000) the future discharge was summarized by computing the median and upper and lower quartiles (from 30 RCM runs) in the two future periods.

Fig. 5 gives an example of the climate change results for the Makona River, which is a typical headwater catchment in the highlands of Guinea. Air temperature is projected to increase by about 1.5°C between 1998-2014 and 2046-2065. Precipitation is projected to increase by about 5%, but there is a large spread in the RCM projections. Nevertheless, there is a clear tendency of RCMs projecting rather an increase than a decrease in precipitation for the Makona River. Due to the increase in precipitation also discharge is projected to increase, as the increase in potential evapotranspiration is not large enough to result in a decrease of discharge in this basin.

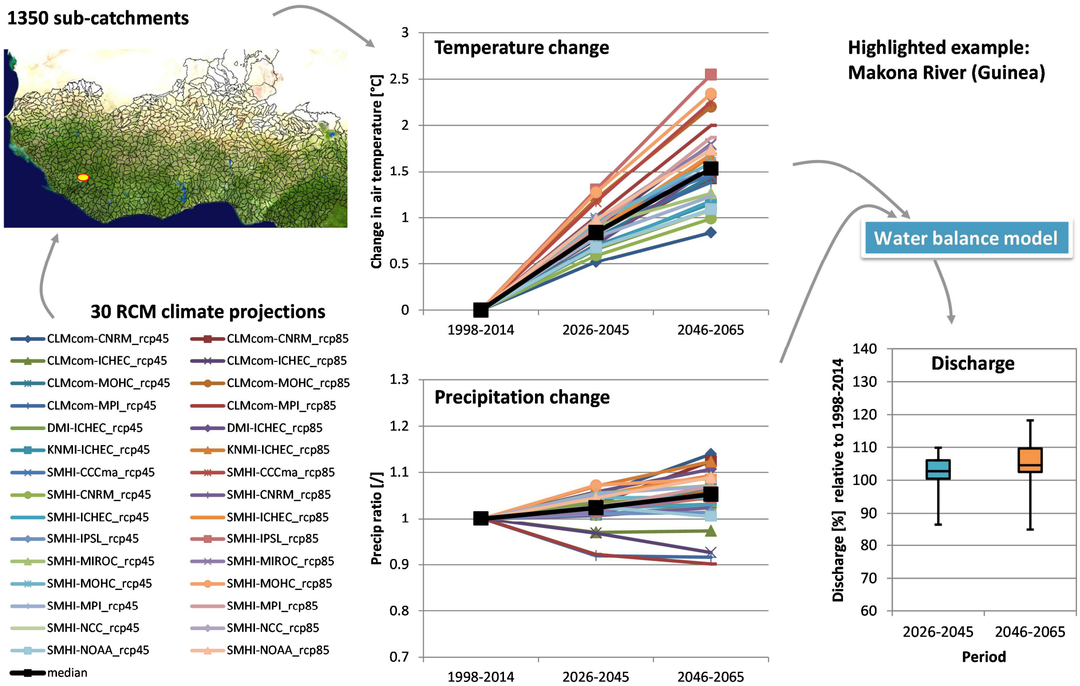

Fig. 5. Expected future annual discharge under climate change projections of air temperature and precipitation. Example for the Makona River in Guinea. The box-plots in the lower right figure show the median, upper and lower quartiles, as well as the maximum and minimum values from the 30 members of the RCM simulation results for future discharge.

We are currently post-processing the large amount of simulation data (500,000 reaches with results for 60 climate change runs) to provide a regional overview of the climate change impact assessment. A first summary of the results shows that there is a general tendency of the climate models to project an increase in rainfall in the Fouta Djallon highlands, where the headwater regions of the Niger, Senegal and Gambia rivers are located. In this region a slight increase in discharge is simulated for the future. In other regions the climate model projections show no consistent signal for changes in future rainfall. However, warming temperatures will increase evapotranspiration and thus reduce runoff. Overall the ensemble median of climate model projections does not suggest that in West Africa there will be considerable decrease in annual discharge in the next few decades.

5. Theoretical hydropower potential

The theoretical hydropower (line) potential is computed for each reach with equation (2), and the specific potential is computed with equation (3). The line potential (units of kW or MW) is the amount of power that would be produced if the full head of the reach was used and if the full discharge was turbinated (i.e. no spillway losses or environmental flow constraints). Therefore, the line potential is an upper limit of possible power generation in this reach. The specific potential (units of kW/km or MW/km) is the upper limit of power that could be generated at a hydropower plant utilizing the hydraulic head of 1 km river reach length.

$$LP_i = 8.5 \cdot Q_i \cdot \Delta H_i \quad (2)$$

$$SP_i = LP_i / L_i \quad (3)$$

where the index i identifies a reach, LP is the line potential in kW, SP is the specific potential in kW/km, Q is mean annual discharge in m^3/s, ΔH is the height difference in the reach in m, L is reach length in km, and the factor 8.5 is used for unit conversion also considering typical turbine efficiency.

The regions with the most promising theoretical hydropower potential are located in Guinea, Sierra Leone and Liberia, as well as in the south-eastern parts of Nigeria. The results are currently classified to identify regions that have attractive hydropower potential for development of:

- Pico/micro/mini hydropower plants with installed capacity < 1MW
- Small hydropower plants with installed capacity 1-30 MW
- Medium/large hydropower plants with installed capacity > 30 MW

The results for river reaches are currently up-scaled to sub-basin and country levels to give a better regional overview. The results for reaches, sub-basins and countries will be made available to the general public via the ECOWREX website of ECREEE (ecowrex.org).

6. Conclusions and outlook

The main conclusions of this study are:

- Availability and reliability of hydro-meteorological data are considerable challenges for water resources assessment in West Africa.
- A simple water balance model proved to be sufficient to estimate the regional distribution of mean annual discharge in all rivers in West Africa. At some of these rivers (Niger, Yobe, Sokoto, etc.) floodplain losses and irrigation withdrawals have to be considered in the model to obtain unbiased discharge simulation results.
- Climate change projections for West Africa do not show a ‘worst-case’ scenario for hydropower development. Future mean annual discharge may actually increase in some parts of West Africa.
- Several West African countries have regions with highly attractive hydropower potential, especially Guinea, Sierra Leone, Liberia and Nigeria.

The results of the study will be published on the ECOWREX website of ECREEE (ecowrex.org) in the second half of 2016. The interactive website presents map layers where users can query the theoretical hydropower potential, longitudinal river profiles, discharge and rainfall data, climate projections, etc. for river reaches, sub-basins and countries. The ECOWREX website allows identification of attractive regions for hydropower development. This allows to focus on selected sub-basins suitable for small hydropower development and to start follow-up site specific studies and targeted discharge measurement campaigns, which are currently under preparation by ECREEE.

Acknowledgements

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